Augmented Reality Assisted Robotic Endovascular Surgery: A Pilot Study

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INTRODUCTION

Cardiovascular diseases, including Abdominal Aortic Aneurysms (AAA), are a major global health concern, causing millions of deaths annually [1]. The standard treatment for AAA involves minimally invasive endovascular surgery, inserting catheters and guidewires through the femoral artery to the target lesion, guided by X-ray Fluoroscopy. Challenges in this procedure include difficulty in manipulating the catheter tip, increased risk of vessel dissection, and reliance on surgeon skills [2]. Robotic platforms, like CathBot developed at Imperial College London, aim to enhance traditional surgery by providing remote manipulation of endovascular instruments, improving accuracy and repeatability [3]. Despite advancements, preventing inadvertent contact between instruments and vasculature remains a challenge. Our work addresses these limitations with a threefold contribution: (1) Development of a surgical scene simulator that aesthetically replicates deformable tissue-instrument interaction, (2) Integration of such simulator with augmented reality (AR) technology and Cathbot, thus introducing the first steps towards a novel guidance system for endovascular navigation that, at this stage of development, could be used by clinicians as a training tool, and (3) Experimentation of the proposed system with users that have no prior experience with AR in guiding the instrument navigation.

MATERIALS AND METHODS

Catheterisation & Tissue Simulations

We used the Obi Softbody plugin for Unity Engine to simulate deformable tissue-instrument interaction. Obi employs Position Based Dynamics (PBD), representing objects as particles and updating their positions iteratively based on constraints. Mesh models of the aorta and catheter were converted into the particle models displayed in Fig. 1. The aorta model features high resolution, incorporating particles with flat and ellipsoidal shapes, while the catheter's particles are rounder, achieving a higher stiffness. The biomechanical model behavior of the aorta was estimated from literature [4] using a stress-strain curve, where the Young's modulus was retrieved from the gradient of the elastic elongation section of the curve. In the simulator, the Young's modulus was estimated empirically, and PBD parameters were finely tuned for visual realism.

Fig. 1 Particle-based models of the abdominal aorta (left) and catheter (right).

Augmented Reality Interface Design

The system is illustrated in Fig. 2. User controls were captured via the keyboard for tip steering, and CathBot through a cylindrical handle for linear and rotary motions, and communicated using LabVIEW to the Unity-based simulator, where the catheterisation is performed. To present the behaviour of the system in an ergonomic fashion to the user, and in hopes of improving the quality and safety of catheterisation, an AR interface was developed and proposed to the user through the Microsoft HoloLens 2 ™ (Microsoft™ Redmond, U.S.A.). Within the interface, the user can visualise 3D views of the catheter and the aorta, but the user is also shown the center line of the aorta, which tends to be the ideal trajectory, to help them navigate. When the user observes that they deviate from the centerline, they can adjust their controls accordingly, avoiding perforations of the lumen wall.
To evaluate the new visualisation system, two additional perspectives were implemented. One aims at mimicking 2D contrast-enhanced Angiographic images without any background information (View 1), while the other offers a closer insight into the local position of the tip in 3D space (View 2), shown in Fig. 3.

Experimental Setup

Six subjects performed the navigation of the catheter through the aorta in each of the three views presented

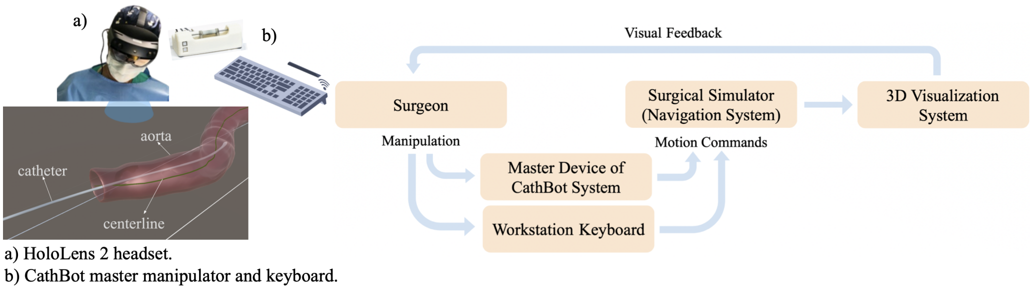

Fig. 2 Schematic of the proposed system. On the left, the system's setup is provided to the user, and on the right, the building blocks of our proposed solution are presented.

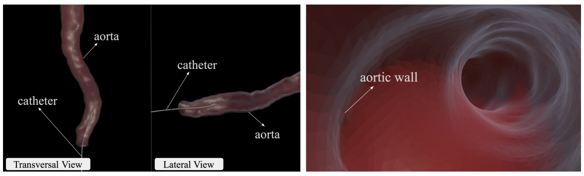

Fig. 3 The left side displays View 1, while the right side features View 2.

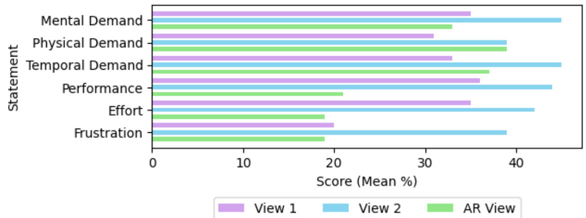

Fig. 5 Results of the NASA TLX questionnaires, with lower scores indicative of better evaluation on the utilised scale.

in a random order. Recorded evaluation metrics included: *forces* exerted by the catheter's tip on the aortic walls during collision (calculated using normal (n), tangent (t), and bitangent (b) components of the impulses, measured from Obi) and the *minimum Euclidean distance*. The total force (F_{tot}) for each aortic particle involved in a collision was computed as follows: $F_{tot}[N] = \sqrt{F_n^2 + F_t^2 + F_b^2}$. The distance ($d$), in Fig. 4, is measured on the x-z plane from the center of mass (com) of the catheter's tip particles to the closest point on the aortic lumen's centerline (c): $d[mm] = min\sqrt{(x_{com} - x_c)^2 + (z_{com} - z_c)^2}$. Users provided subjective assessments through three *NASA TLX questionnaires*, one for each visualization type.

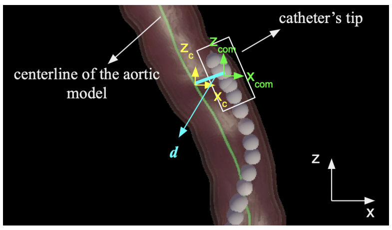

Fig. 4 Distance d on the x-z plane between the center of mass of the particles composing the catheter's tip and the closest point of the aortic model center line.

RESULTS AND DISCUSSIONS

Parameter tuning allowed us to achieve a good aesthetic representation of deformable tissue-instrument interaction. The user study revealed that the lowest values across all metrics were obtained, with statistically significant differences, with AR guidance, as shown in Table I. The AR view also reported lower measurement variance compared to the other two view modalities, indicating more predictability, stability, hence highlighting the improvement in catheterisation safety, as parameters can be better controlled. Regarding the other two views, no clear difference or improvement of one over the other can be deduced.

In Fig. 5, the subjective assessment conveyed that users perceived better performance, reduced effort, and frustration when using AR. The lower mental demand suggested that the system is comparatively intuitive and easy to use, while the slightly higher physical demand indicates that there is room for improvement, perhaps by integrating steering into CathBot.

TABLE I Results of the experiments reporting the median and maximum values of forces (per particle) and distances for each of the three visualisation modes.

	View 1	View 2	AR View
Median Force [N]	0.133 ± 0.117	0.167 ± 0.055	**0.079 ± 0.033**
Max Force [N]	0.456 ± 0.326	0.526 ± 0.092	**0.329 ± 0.095**
Median Dist [mm]	1.244 ± 0.158	1.188 ± 0.239	**0.070 ± 0.019**
Max Dist [mm]	2.603 ± 0.116	2.457 ± 0.135	**0.320 ± 0.024**

CONCLUSION

In this research, we proposed a first study towards an AR visualization system for endovascular robotic surgery navigation, achieving promising results. Further developments may explore reinforcement learning for path planning and integration into real practice by registering holograms to reality and including the guidewire as input.

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